THEORY AND PERFORMANCE OF THE ICONOSCOPE*

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SUMMARY

Field tests have shown the present standard iconoscope to be a very satisfactory television pick-up device. However, from a theoretical point of view the efficiency of the iconoscope as a storage system is rather low. The principal factors responsible for the low efficiency are lack of collecting field for photo-electrons, and losses caused by the redistribution of secondary electrons produced by the beam.

Limits to the sensitivity of the standard iconoscope are set by the ratio of picture signal to amplifier and coupling-resistor "noise." Experimental and theoretical determinations indicate that an excellent picture can be transmitted with from 2½ to 6 millilumens per cm^2 on the mosaic.

Two methods are considered by which the sensitivity may be increased. The first is by the use of secondary-emission signal-multipliers and a low-capacitance mosaic, while the second makes use of secondary-emission image intensification. The sensitivity limits for the two cases are calculated.

INTRODUCTION

Experimental tests on the present standard iconoscope camera, illustrated in Fig. 1, have shown the iconoscope to be a very satisfactory television pick-up device. These tests include not only laboratory measurements but also extensive field tests by the National Broadcasting Co. at Rockefeller Centre, New York City. The conclusion arrived at from these tests is that the iconoscope is sufficiently sensitive to be used for outdoor pictures under a wide range of weather conditions, and in the studio without the need of unbearable illumination. However, it would be advantageous for both uses to have somewhat greater sensitivity. The following discussion, as well as dealing with the theory of operation of the standard iconoscope, describes two methods which have resulted in a marked increase in sensitivity. The tubes described are, however, still in the laboratory stage and not as yet ready for use in a commercial television system.

The principles and construction of the standard iconoscope, together with its associated equipment, have been described in detail elsewhere,† and a very brief description for the sake of continuity should suffice. The iconoscope consists of a photosensitive mosaic and an electron gun, assembled in a glass bulb which is highly evacuated. The electron gun is made up of an indirectly heated oxide-coated cathode, a control grid, a cylindrical first anode, and a second anode, also cylindrical but slightly larger in diameter. The gun assembly is shown diagrammatically in Fig. 2. This gun functions as an electron optical system for producing a narrow bundle of electrons which is made to scan the mosaic by means of magnetic deflecting coils.

The mosaic consists of a thin sheet of mica coated with a conducting metal film on one side, and covered on the other with a vast number of tiny, photosensitized silver globules. This mosaic is mounted in the blank in such a position that the electron beam strikes the photo-sensitized side at an angle of 30° from the normal, and the optical image to be transmitted is projected normal to the surface on the same side. The arrangement of these elements in the tube is shown in Fig. 3, while Fig. 4 shows an iconoscope with optically flat window.

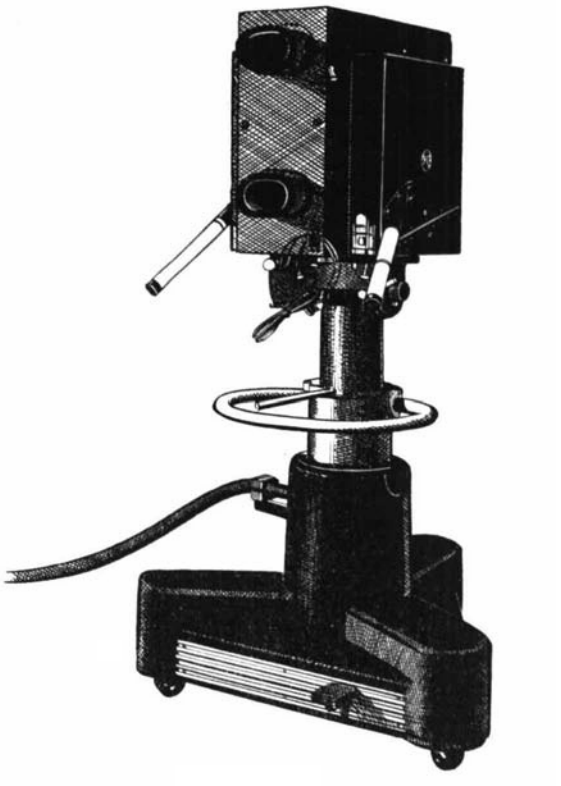

Fig. 1

Briefly, the iconoscope mosaic may be thought of as a 2-dimensional array of tiny photocells, each shunted by a condenser which couples them to a common signal lead. When the mosaic is illuminated these condensers are charged positively with respect to their equilibrium potential owing to the emission of photo-electrons from the photosensitive elements. For any particular element, this charging process continues for a time equal to

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† See Reference (1).

the picture-repetition interval, i.e. until the beam in the process of scanning returns to the element. When the beam strikes it, it is driven to equilibrium, releasing its charge and inducing a current impulse in the signal

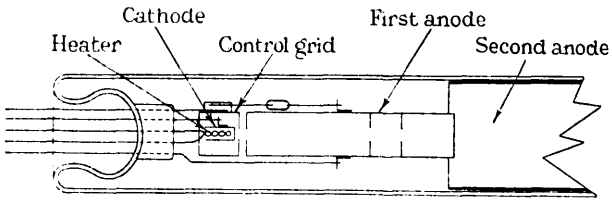

Fig. 2.—Electron gun.

lead. The train of impulses thus generated constitutes the picture-signal output of the iconoscope. This description serves to illustrate the general principles of the iconoscope, but is not sufficiently accurate to form the basis of an analysis of its operation.

MECHANISM OF OPERATION OF THE ICONOSCOPE

In considering the operation of the iconoscope, because of the fact that the silver globules are so small that a great number of them are under the beam at any instant the mosaic may be treated as a continuous surface which has infinite transverse resistance, and which has both a high secondary-emission ratio (in the neighbourhood of 5 to 7) and a good photosensitivity. This surface has a capacitance of about 100 $\mu\mu$F per cm^2 in the case of a standard tube. Considered in this way, it can be readily seen that the picture element is a purely fictitious concept when applied to the mosaic. Thus, instead of discussing the behaviour of discrete photo-electric elements, we shall deal with the mosaic as though it were a 2-dimensional continuum.

The average potential of the mosaic under bombardment, while no light is falling upon it, is between 0 and 1 volt negative with respect to the elements which collect

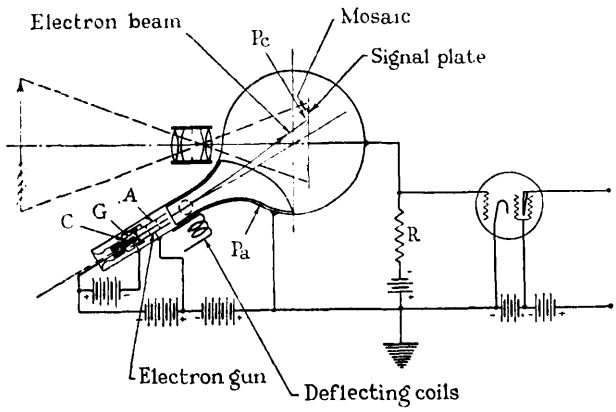

Fig. 3

the secondary emission from the mosaic, i.e. the second anode. However, the potential is not uniform over the entire surface. The area directly under the scanning beam will be at a potential of + 3 volts with respect to the second anode, this being the potential at which the secondary-emission ratio from caesiated silver becomes unity. Away from the point under immediate bombardment in the region which has just been traversed by the scanning beam the potential will be found to decrease, until at a distance equal to 25 %–30 % of the

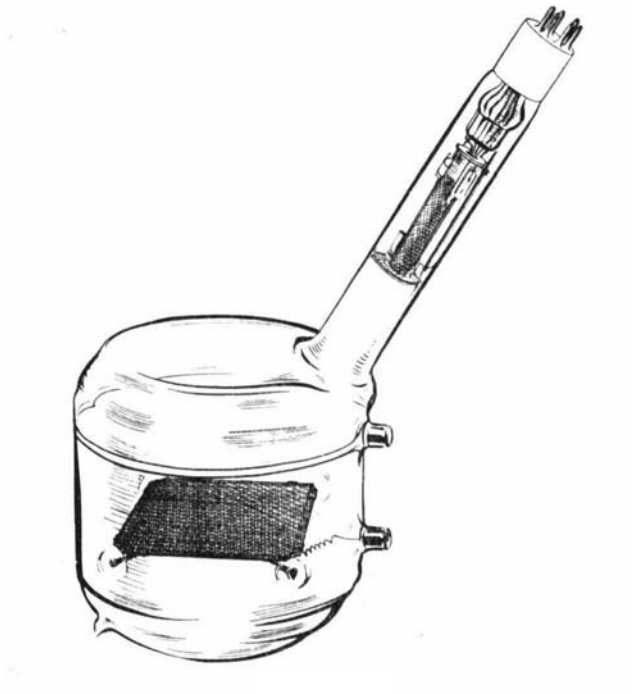

Fig. 4

vertical scanning distance the potential reaches about − 1½ volts with respect to the second anode. The rest of the mosaic is at this potential. This decrease in potential is caused by electrons which leave the point under bombardment and return to the mosaic as a more

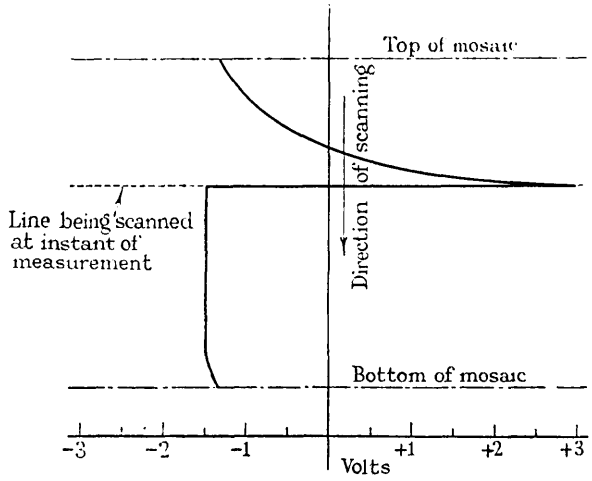

Fig. 5.—Instantaneous potential of the mosaic.

or less uniform rain of low-velocity electrons. Fig. 5 shows a map of the instantaneous potential distribution over the mosaic.

The scanning beam sweeping over the mosaic acts like a resistive commutator. The resistance in this case is determined by the current/voltage relation of the

secondary electrons from the bombarded point. While this resistance is actually non-ohmic, we shall not introduce appreciable error if we assume it ohmic over the small voltage-range dealt with in the case of the iconoscope. Experimental measurements show this beam impedance, Z, to be given by the relation $Z = Z_0/i_b$, where i_b is the beam current and Z_0 is the coefficient of beam impedance. Z has a value between 1 and 2 ohm/ampere.

For purposes of computation, the beam current will be taken as 0·5 microampere, the spot as a square of 0·025 cm. side, and the linear spot velocity as $1{\cdot}6 \times 10^5$ cm. per sec.

Any small element of area, ds, of the mosaic when it is swept over by the scanning beam must change its potential from $-1\frac{1}{2}$ volts to its equilibrium value of approximately $+3$ volts. The capacitance of this area will be $C = C_0 ds$, where C_0 is the capacitance per unit area. The impedance through which this capacitance is discharged will be $Z = Z_0/(\rho ds)$, ρ being the current density of the beam. The equation of the discharge will therefore be

$$V = \left[V_2(xy) - V_1(xy)\right]\left[1 - e^{-t\rho/(C_0 Z_0)}\right] \quad . \quad (1)$$

In this equation, V = change in potential of ds, $V_2(xy)$ = equilibrium potential at point xy under beam, $V_1(xy)$ = potential before bombardment, and t = time.

In order that the elements may reach equilibrium, the condition

$$V \simeq V_2 - V_1$$

must be fulfilled. For this to be true, the relation

$$\frac{Z_0 C_0}{\rho} < T$$

(where T = length of time for which the beam is on the element ds, or
$T = h/V$, where h is the spot diameter and V is the beam velocity)

must be satisfied. From the operating conditions, we find that $T = h/V = 1{\cdot}5 \times 10^{-7}$ sec. and $Z_0 C_0/\rho = 1{\cdot}2 \times 10^{-7}$ sec. Thus the requirements for establishing equilibrium are fulfilled.

In the above expression both V_1 and V_2 are given as functions of the co-ordinates of the mosaic, x and y. This is because both the equilibrium under the beam and the equilibrium away from the beam are not constant over the surface.

The net current leaving the elemental area under these conditions will be

$$di_e = -\left(C_0 \frac{dV}{dt}\right)ds \quad . \quad . \quad . \quad . \quad (2)$$

Since the beam current reaching the element is $-\rho ds$, the total current from the element is

$$di_t = -\left(\rho + C_0 \frac{dV}{dt}\right)ds$$

This entire current will not reach the second anode because, on the average, as much current must reach the mosaic as leaves it. Let $\chi(xyV)$ be the fraction of this current which reaches the second anode; then the current to the second anode can be written as

$$di_s = \chi(xyV)\left(\rho + C_0 \frac{dV}{dt}\right)ds \quad . \quad . \quad . \quad (3)$$

The instantaneous current, i_s, reaching the second anode, is given by the integral of the above expression over the area of the scanning beam. Since the current i_s carries the picture signal, the solution of equation (3) would be very desirable. This integration, however, cannot be performed since the function $\chi(xyV)$ is not known.

It is possible to make certain approximations which will enable the calculation to be made of an average value for the redistribution function. Since the mosaic is an insulator, the average value of its function must be given by

$$\bar{\chi} = \frac{i_b}{i_T} = \frac{i_b}{i_b + i_s} \quad . \quad . \quad . \quad . \quad . \quad (4)$$

In this equation, i_b is known and i_e can be found as follows:—

$$i_e = \int C_0 \frac{dV}{dt} ds$$

But we have

$$V = \left[V_2 - V_1\right]\left[1 - e^{-t\rho/(C_0 Z_0)}\right]$$

and

$$\frac{dV}{dt} = (V_2 - V_1)\left(\frac{\rho}{C_0 Z_0}\right)e^{-t\rho/(C_0 Z_0)}$$

$$ds = hV dt$$

Therefore we can write

$$i_e = \frac{hV\rho}{Z_0}(V_2 - V_1)\int_0^T e^{-t\rho/(C_0 Z_0)}dt$$
$$\simeq hVC_0(V_2 - V_1)$$

and

$$\bar{\chi} = \frac{1}{1 + \dfrac{hVC_0(V_2 - V_1)}{i_b}} \quad . \quad . \quad . \quad (5)$$

Evaluating this function, using the constants of the iconoscope, we find that $\bar{\chi} \simeq 0{\cdot}25$. This means that, out of the total charge released by an element when struck by the beam, only about 25 % will reach the second anode, the remainder being returned to the mosaic. In other words, only about 25 % of the stored charge is available for producing the picture signal.

As was mentioned above, $V_1(xy)$, $V_2(xy)$, and $\chi(xyV)$ are not constant over the mosaic, even when it is in darkness. As a consequence, there is a variation in the current reaching the second anode as the mosaic is scanned. This gives rise to a spurious signal which, if not compensated, produces irregular shading over the picture. The importance of this spurious signal is sufficient to warrant further discussion. It is evident from the nature of the factors upon which it depends that it may be regarded as divided into two parts. The first is the stored signal, which depends upon $V_1(xy)$, while the second is an instantaneous effect, depending upon the variation of $V_2(xy)$ and $\chi(xyV)$ over the mosaic.

The instantaneous component can be demonstrated very strikingly if a metal plate is substituted for the mosaic in an iconoscope. When this plate is scanned in the ordinary way, it being maintained at a potential close to

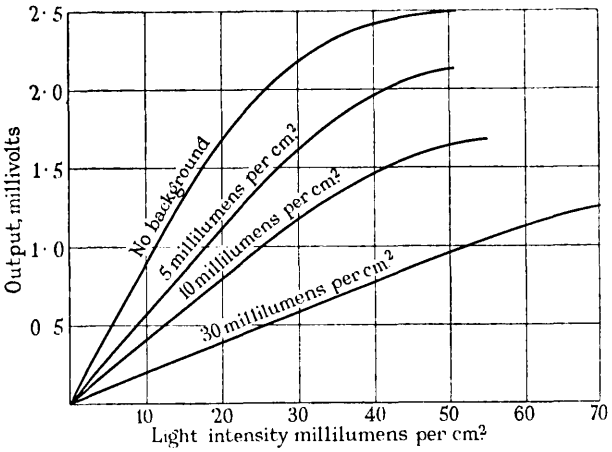

Fig. 6.—Variation of output with light intensity, for different values of background illumination.

that of the second anode, a spurious signal is produced very similar to that from the mosaic. While the mechanism of generation of this signal is not exactly the same as that in the case of the mosaic, it is quite similar. If the potential of the plate is made negative or positive with respect to the second anode, the secondary emission will be suppressed, or saturated, and the signal will disappear. In practice, the spurious signal from the iconoscope is compensated for by means of an electrical correcting network. Considerable work has been done, and further work is in progress, on methods of overcoming the effect of the spurious signal or entirely eliminating it.

When an optical image is projected on to the mosaic, the illuminated area emits photo-electrons in proportion to the light falling on it. As a consequence, this area reaches a less negative final potential than an unilluminated area. In this connection it should be pointed out that, although the mosaic receives a continuous redistribution current, this current is very little altered by small changes in potential over small areas. In other words, the impedance shunting any element is very high. As a result of the difference in $V_1(xy)$ for an illuminated and an unilluminated region, there is a change in i_s. This fluctuation constitutes the picture signal.

Besides the inefficiency consequent on the redistribution losses, the photo-emission is also inefficient owing to the small fields drawing the photo-electrons away from the mosaic. The effective photo-emission of the mosaic in the standard iconoscope is only about 20 % to 30 % of its saturated value. This means that the overall efficiency of the iconoscope is only 5 % to 10 %. In spite of this inefficiency, the great advantage resulting from the use of the storage principle makes the iconoscope a very effective pick-up device.

Before we leave the discussion of the mechanism of operation of the iconoscope, mention should be made of the phenomenon of line sensitivity which results from the variation in potential over the surface of the mosaic. Referring to Fig. 5, it will be seen that the line on the mosaic just ahead of the scanning beam is subject to a strong positive field, and consequently has high photo-electric efficiency. The line is, in consequence, extremely sensitive. This can be demonstrated very strikingly in the following way. The image from a continuously-run motion-picture film (e.g. a picture projected by a moving-picture machine from which the intermittent shutter has been removed) is projected on to the mosaic of the iconoscope. The film is run at such a rate that the frame speed is equal to the picture frequency, and in

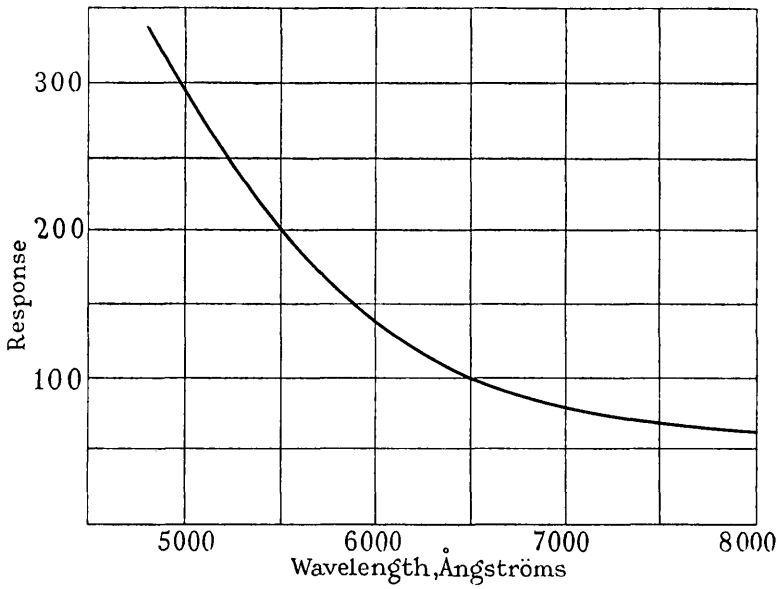

Fig. 7.—Colour response of standard iconoscope.

such a direction that the picture moves in the opposite direction to that of scanning. Under these conditions the iconoscope is found to transmit a clear image of two frames of the moving-picture film, although to the eye there appears to be only a blur of light on the mosaic.

From the above description of the mechanism of operation of the iconoscope it is apparent that the efficiency decreases as the light intensity increases. Fig. 6 shows a family of measured curves illustrating this effect. The output is measured in millivolts across a 10 000-ohm coupling resistance, and the light input in lumens per cm^2 on the mosaic. The curve showing the greatest response represents the signal output from a small illuminated area when the remainder of the mosaic remains unilluminated. The effect of a background illumination over the entire mosaic is shown by the remaining curves of the family.

The colour response of an iconoscope depends upon the activation schedule and the operating conditions involved. Fig. 7 shows the colour response measured on the present type of standard iconoscope.

CALCULATION OF THE SENSITIVITY OF THE ICONOSCOPE

So far, we have considered only the magnitude of the signal output. If it were possible to amplify the signal output indefinitely without introducing spurious effects, the problem of attaining high sensitivity would merely be one of increasing the amplifier gain. However, the picture amplifier amplifies not only the signal output from the iconoscope but also the voltage generated by the thermal agitation in the coupling resistor (or other coupling device). If the voltage generated by the picture signal becomes of the same order as these fluctuations, the picture becomes lost in " noise." This sets a definite limit to the sensitivity that can be obtained.

In making any calculations concerning the sensitivity of the iconoscope we are faced with the problem of assigning quantitative values to the psychological effect of picture/noise ratio. Tests have been made to determine the effect on the observer of various ratios of peak picture-signal in an average picture, to root-mean-square noise. It has been found that if the r.m.s. noise is equal to 30 % of the picture signal, the picture is still recognizable, but the resolution is decreased and the picture is tiring to watch. In addition, if the ratio remains constant but the picture amplitude is decreased, the noise becomes less objectionable; however, there is no increase in the effective resolution. If the picture/noise ratio is 10 : 1, a very good picture can be obtained but the noise is still very noticeable. Such a picture is completely usable and has fair entertainment value. When the noise is reduced to 3 % of the picture, it becomes practically unnoticeable and the picture may be regarded as excellent.

Let us base our calculation of sensitivity on an allowable noise/picture ratio of 10 %. While under these conditions the amount of noise would be greater than would be tolerated if conditions made it possible to avoid such a high noise/picture ratio, nevertheless such a picture would have reasonably good entertainment value and could be broadcast, particularly where programme continuity made transmission necessary. To make the calculation the following data are necessary: Area of mosaic (A), 128 cm^2; photosensitivity (p), 7 μA per lumen; overall efficiency (k), 0·05; coefficient of thermal e.m.f. (K_1), $1{\cdot}6 \times 10^{-20}$; coupling resistance ($R$), 10 000 ohms; frequency band (f), 2×10^6 cycles per sec.

If the region of maximum illumination receives a light flux F lumens per cm^2, the signal from the iconoscope from this point will be

$$I = Fpk\frac{A}{n}\frac{T_0}{T} \quad . \quad . \quad . \quad . \quad . \quad (6)$$
$$= FpkA$$

where n = number of elements, T_0 = picture (frame) time, and T = time for which the beam is on one picture element. But, since $T_n = T_0$, and substituting the values given above, the instantaneous current pulse is

$$i_s = 4{\cdot}5 \times 10^{-5}F \text{ amp.}$$

Since this is fed through a 10 000-ohm resistor, the picture voltage is

$$V_s = 0{\cdot}45\,F \text{ volts}$$

The coupling resistor alone does not generate the entire noise found in the picture amplifier. Noise voltages generated in the first amplifying valve and first plate resistor are each present in appreciable amount, particularly in an amplifier covering as broad a frequency band as is required. In order to take into account these factors, it will be assumed that the noise in the amplifier is equivalent to a resistance of 30 000 ohms across the input. The noise voltage will therefore be

$$V_N^2 = K_1 fR$$
$$= 9{\cdot}6 \times 10^{-10}$$

or an r.m.s. noise voltage of

$$\overline{V}_N = 3{\cdot}1 \times 10^{-5}$$

The picture/noise ratio under these conditions is therefore

$$N = 1{\cdot}45 \times 10^4 F$$

Further, if the minimum usable ratio is assumed to be 10, the smallest amount of light falling on the mosaic sufficient to give an adequate picture will be 7×10^{-4} lumen per cm^2. This corresponds to illumination on the high lights, and is of course somewhat higher than the average illumination of the picture. On the same basis, the illumination required to produce an excellent picture, i.e. where the noise is only 3 % of the picture signal, would be as follows: $N = 1{\cdot}45 \times 10^4 F = 33$; $F = 2{\cdot}3 \times 10^{-3}$ lumen per cm^2. Actual measurements on an average iconoscope show that an excellent picture can be transmitted from an object having a surface brightness of 20 to 50 candles per sq. ft., using an $f/2{\cdot}7$ lens. The illumination on the mosaic under these conditions will be:—

$$F = \frac{\pi B}{4(\text{Focal length of lens})^2} = 2\tfrac{1}{2} \text{ to } 6 \text{ millilumens per cm}^2$$

When allowance is made for reflection losses in the

optical system and for the psychological element, the agreement will be seen to be fairly good.

METHODS OF INCREASING THE SENSITIVITY OF THE ICONOSCOPE

The problem of increasing the sensitivity of the iconoscope may be approached in three different ways: First, by keeping the signal sensitivity the same and reducing the noise generated; second, by increasing the quantity of charge per unit light flux acquired by the mosaic; third, by increasing the overall efficiency of the iconoscope. The third method has been studied extensively, and laboratory iconoscopes have been made with efficiencies as high as 50 %. This work is still in the early experimental stage, however, and will not be discussed here.

Let us consider the first method of increasing the sensitivity. Noise reduction is possible because of the fact that the effective circuit carrying the signal from the iconoscope is completed through the secondary emission from the mosaic. In other words, when the coupling resistor and amplifier are connected to an electrode which collects the secondary emission, a signal can be obtained which is equal to that from the signal plate. If these secondary electrons are led into a secondary-emission multiplier instead of being collected, it is possible to obtain the signal from the multiplier and thus completely eliminate the noise that would be introduced by the conventional coupling-resistor and amplifier.

Before taking up the question of the type of multiplier suitable for this purpose, or the methods used to get the electrons from the mosaic into the multiplier, let us consider the sensitivity and noise relations resulting from this scheme. The picture output will be equal to the signal at the mosaic times the gain of the multiplier; the latter will be written as B^n, B being the gain per stage and n the number of stages. Hence

$$I_s = FpkAB^n$$

On the other hand, the noise will be essentially the shot noise in the secondary emission from the mosaic. More exactly, the noise* is

$$I_N^2 = \frac{B^{2n+1}}{B-1} K_2 f \cdot 2i_b$$

Therefore, the picture/noise ratio will be

$$N = \frac{I_s}{I_n} = \frac{kA}{\sqrt{(K_2 f)}} \sqrt{\left(\frac{B-1}{2B}\right)} \frac{F}{\sqrt{i_b}} \quad . \quad . \quad (7)$$

Evaluating this, we find

$$N \simeq 40 \frac{F}{\sqrt{i_b}}$$

In actual practice the beam current in a standard iconoscope is about 0·5 microampere. If N is assumed to be 10, the illumination required will be

$$F \simeq 2 \times 10^{-4} \text{ lumen per cm}^2$$

This is to be compared with the result where a normal amplifier was used, and where the illumination was 7×10^{-4} lumen per cm^2; that is, this represents an increase in sensitivity of about 3 times.

The interesting point about this multiplier iconoscope is, however, that its sensitivity depends upon the beam current; therefore, if we can reduce the beam current without decreasing the efficiency, the iconoscope becomes more effective. It is not possible, in a multiplier iconoscope using a standard mosaic, to reduce the beam current without loss in efficiency owing to the increase of discharge time of the elements. When this condition occurs, the efficiency falls off and, furthermore, moving objects blur. In order to decrease the time-constant so that the beam current can be decreased, it is necessary to reduce the element capacitance. The simplest method of accomplishing this is by using a thicker insulating layer for the mosaic. Assuming that the time-constant is fixed, the beam current should be inversely proportional to the capacitance; in other words, approximately proportional to the mosaic thickness. It

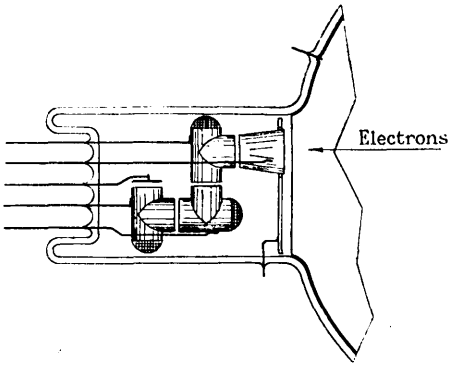

Fig. 8.—" T " type multiplier.

is interesting to carry the calculation down to the limiting case and to see what is the maximum sensitivity obtainable by this method. Obviously, the beam current cannot be reduced beyond the point where it becomes equal to the photocurrent. Under these conditions, we can calculate the sensitivity as follows:—

$$i_{phot.} = k'Fpah$$

where a and h are the length and height of the region considered, and k' is the fraction of photocurrent leaving the mosaic. The instantaneous beam equivalent must therefore be

$$i_0 = k'Fpah\frac{T_0}{Ta} = FpAk'$$

$$I_s = FpkA$$

Hence the picture/noise ratio will be

$$N = \frac{I_s}{I_n} = \frac{pkA}{\sqrt{(k_2 f)}} \sqrt{\left(\frac{B-1}{B}\right)} \frac{F}{\sqrt{2FpAk'}} \quad . \quad (8)$$

$$= \sqrt{\left[\frac{pk^2A(B-1)}{2k'K_2fB}\right]} \sqrt{F}$$

Assuming, as before, that N must be at least 10, the minimum light that can be used will be $F = 5 \times 10^{-6}$

* See Reference (2).

lumen per cm^2. This would be the smallest amount of light that would suffice to transmit a satisfactory picture when noise suppression of this type was used. The value for the sensitivity just given must be regarded purely as a theoretical estimate. In practice, no tube has yet been made based on this principle with a sensitivity greater than 10 to 20 times that of the standard iconoscope.

Having arrived at certain theoretical conclusions as to the ultimate sensitivity that can be attained, let us now consider the practical details of construction. The multiplier suitable for this purpose is preferably one which does not involve the use of a magnetic field: it must be capable of multiplying a comparatively broad beam of electrons rather than a sharply defined spot, and must have a high gain per stage. It has been found that the " T " type* multiplier, whose construction is shown in Fig. 8, serves very adequately. There are, however, a number of possible types of multipliers that might be used.

In order to get the electrons away from the mosaic, a disc—run at from 25 to 100 volts positive with respect to the second anode—is placed at the entrance of the protuberance containing the multiplier. This disc is perforated with an aperture behind which is mounted a small truncated cone at a high positive potential, carrying the electrons through the aperture and into the multiplier. The disc, because of its area, determines to a great extent the field close to the mosaic, while the cone governs the field distribution close to the disc.

Several tubes were made to determine the most suitable location for the multipliers, with the results shown in the Table in col. 2 on this page.

Because of optical reasons, it is a difficult problem to locate the multiplier directly in front of the mosaic. It was found, however, that two multipliers located at 30° on either side of the normal to the mosaic, collected all of the electrons leaving the mosaic. This type of iconoscope is shown in Fig. 9. While work is still being done on this development, very satisfactory pictures under conditions of low illumination have been obtained from this type of tube. The principal problems yet to be dealt with are those of activating the multipliers and the mosaic simultaneously, and of obtaining a uniform distribution of the picture.

The second method of increasing the sensitivity of the iconoscope is by the use of secondary-emission image intensification. This can be accomplished by allowing the electron image produced in some form of image tube to fall on a mosaic constructed in such a way that the elements extend through the mosaic. The elements on the side of the mosaic on which the electron image is projected are made secondary-emissive, so that for every electron striking the mosaic 6–8 electrons are emitted. Thus, the stored signal will be several times that which would be due to the original photo-electric current. The scanning beam sweeps across the back of the mosaic, removing the stored picture in the same way that the picture is removed from the ordinary one-sided mosaic. The gain in sensitivity will be proportional to the intensification at the mosaic. Furthermore, it is possible to produce semi-transparent photocathodes of the type used in the image tube with more than twice the photo-sensitivity of the ordinary mosaic. Considering both

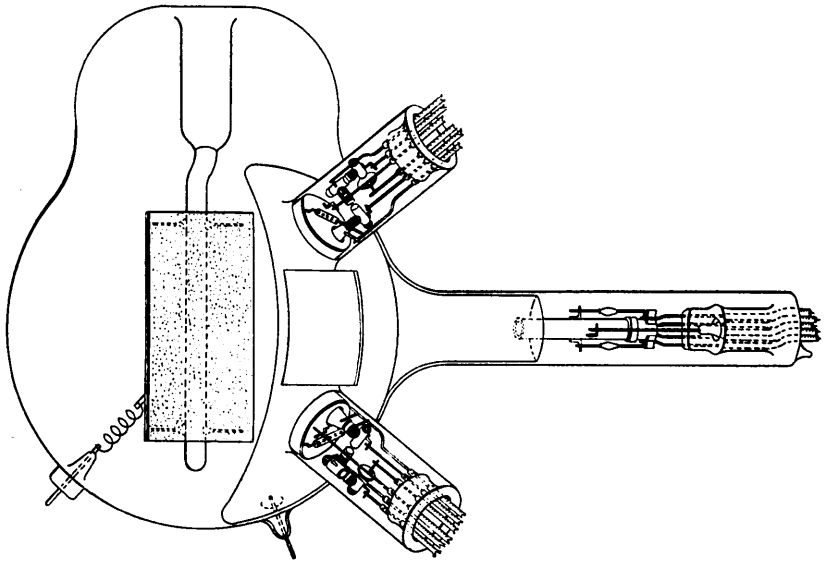

Fig. 9.—Signal-multiplier iconoscope.

Position	Percentage of electrons collected
Behind mosaic	10
Side of mosaic	50
At angle of 30° to normal	80
Front	100

* See Reference (2).

these factors, it is possible to increase the sensitivity by from 10 to 15 times.

Before examining the details of this type of tube, let us consider the limiting sensitivity that can be attained in this way. First, the gain obtainable is not of course limited to that which can be obtained from one stage of secondary-emission multiplication. It is perfectly possible, and has been accomplished in experimental tubes, to allow the electron image from an image tube to fall upon a secondary-emitting surface, and with a second electron optical system to refocus this enhanced image. Let us assume that this process can be repeated as many times as is desired, and the multiplied image be projected on a two-sided mosaic. In this way, the charge image stored on the mosaic may be made as large as is desired. However, as was the case with the low-capacitance tube, there are definite limits to the sensitivity that can be attained. The limit in this case is due to the statistical fluctuation in the photocurrent emitted from the photo-

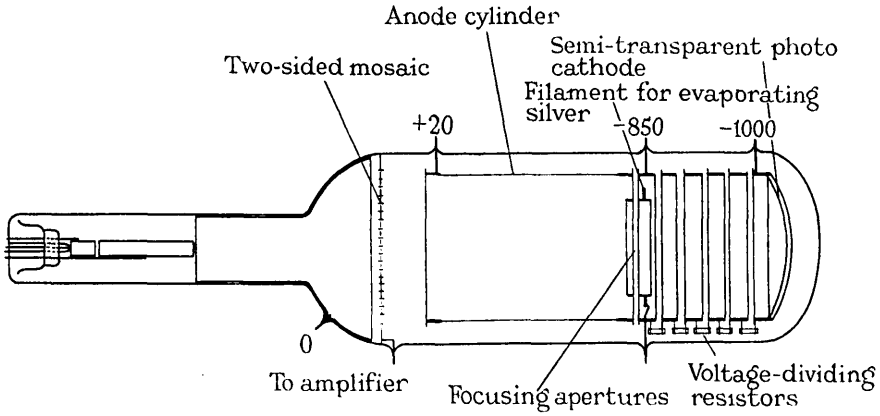

Fig. 10.—Image-multiplier iconoscope.

sensitive cathode upon which the image is initially projected.

In order to estimate the ultimate sensitivity, let us assume that the gain of each stage of the secondary-emission multiplier is sufficiently great for the picture/noise ratio at the cathode to be not appreciably greater than it is at the mosaic. This is equivalent to assuming that the fraction $(B - 1)/B$, used above in multiplier calculations, is equal to unity, which is amply justified when gains of 7 or 8 per stage can be obtained. It can be shown that, if q is the photo-electric charge emitted by one picture element during one frame time, the mean-square fluctuation will be

$$\bar{q}_N^2 = eq$$

If, as before, we assume that the root-mean-square fluctuation should be 10 % of the total charge, we have

$$N = \frac{q}{q_N} = \frac{q}{\sqrt{(eq)}} = \frac{i_p T_0}{\sqrt{(e i_p T_0)}}$$

But

$$i_p = Fap = \frac{FAp}{n}$$

where i_p is the photo-emission from one element, and a the area of an element. Thus, we have

$$N = \sqrt{\left(\frac{FApT_0}{en}\right)}$$

It can be demonstrated, by means of a Fourier transformation, that $T_0/n = 1/(2f)$; hence we may write

$$N = \sqrt{\left(\frac{FAp}{2ef}\right)}$$

Actually, the picture/noise ratio should have been written

$$N = \sqrt{\left(\frac{FAp}{2ef(1 + k'')}\right)}$$

where the factor k'' takes into consideration the fluctuations in the entire group of multiplied photo-electrons which strike the mosaic and induce "noise" directly on the signal plate. The value of k'' depends on a great many variables. Its value cannot be less than unity, and for the purpose of calculation will be assumed to be in the neighbourhood of 10.

On this basis, the limiting amount of light which will produce a picture signal equivalent to 10 times the r.m.s. noise will be

$$F = \frac{2ef(1 + k'')N^2}{Ap}$$

$$= 7 \times 10^{-7} \text{ lumen per cm}^2 \quad . \quad . \quad (9)$$

For the case just considered it would require an image multiplication of 500–1 000 to reach the limiting sensitivity. It is interesting to note that this limit is of about the same order of magnitude as for the case of the low-capacitance iconoscope. In general, it is possible to show that the limiting light sufficient to give a picture/noise ratio of N for an ideal storage television system (where the conversion efficiency is 100 %) will be

$$F = \frac{2efN^2}{Ap} \quad . \quad . \quad . \quad . \quad . \quad (10)$$

While experimental tubes have been made with more than one stage of image multiplication, this technique

has not been developed to a sufficient extent to be applicable to a commercial iconoscope in use in the television field test.

Very successful single-stage image-multiplier iconoscopes have been built. Fig. 10 shows diagrammatically such a tube. It consists, essentially, of an electron image tube* which projects on to a secondary-emissive mosaic an electron reproduction of an optical image formed on the photocathode. The mosaic in this instance differs from that in the standard iconoscope in that the mosaic elements extend through the insulating matrix in such a way that the electron image can be formed on one side while the mosaic is scanned on the other. If the mosaic is scanned while the photocathode is in darkness, the potential of each element will be nearly the same as that of the second anode, owing to the action of the beam and the redistribution of electrons.

When light is projected on to the photocathode, electrons will be emitted. These electrons are accelerated by the electron optical system and refocused on the mosaic. Each element thus bombarded will emit secondary electrons which will be drawn to the anode cylinder, since the latter is at a positive potential with respect to the mosaic. If the secondary-emission ratio of an element is, for example, B, the net current to it will be $(B - 1)$ times the primary current incident upon it. It should be pointed out, however, that the average amplification of the mosaic will not be $(B - 1)$, owing to the fact that the elements do not cover the entire surface under the electron image. If c be the fraction of the surface covered by the elements, then the effective gain will be $c(B - 1)$.

The electron optical part of this iconoscope is identical with the electron image tube, for which purpose the latter was developed. It consists of a semi-transparent photocathode; a cathode cylinder composed of five rings, each at a successively higher positive potential; and an anode cylinder which is maintained at approximately 1 000 volts positive. The lens of this system may be regarded as being located between the cathode and the anode cylinder, though actually it is a thick lens occupying a considerable portion of the total length of the system. The magnification of such a system can be shown† to be $m = v/(2u)$, where u and v respectively are the object and image distances from the lens. For the type of tube illustrated, where unity magnification of the image is used, the length of the cathode cylinder is half that of the anode cylinder.

The cathode is curved, with a radius equal to the lens diameter. This curvature not only corrects for image distortion and for curvature of the image field but also reduces the astigmatism to such an extent that it no longer limits the resolution in any part of the field.

The semi-transparent photo-electric surface used is caesium on oxidized silver. It is formed by evaporating a thin layer of silver on to the cathode disc from a filament located directly behind the aperture forming the electron lens. This silver is then oxidized by means of an electric discharge in oxygen at a low pressure, until the layer becomes almost completely transparent. Caesium is admitted, and the tube is baked exactly as is done in activation of a photo-electric cell. As a final step, additional silver is evaporated on to the surface and the tube is again baked. This final silver sensitization not only increases the photosensitivity and conductivity of the film, but also adds to its stability. This type of surface will have a photo-sensitivity of 20 to 25 microamp. per lumen, and a colour response very similar to that of a caesium photocell.

The most difficult item in the image-multiplier iconoscope to construct is the mosaic. One method by which a suitable mosaic can be built is as follows: A fine-mesh, electrodeposited nickel screen forms the base. It is coated with a thin layer of special vitreous enamel in such a way that its entire surface is completely insulated. The interstices in the screen are then filled with silver oxide made into a paste with an appropriate binder. The screen is finally heated to a temperature just under the melting point of the enamel in order to drive off the binder and to reduce the silver oxide to metallic silver. The arrangement of the elements and the actual construction of this type of tube will be clear from Fig. 10.

Actual tests on this type of iconoscope show that its sensitivity is about 10 times greater than that of a standard iconoscope. This added sensitivity is due, in part, to the secondary-emission multiplication and, in part, to the greater photosensitivity of the light-sensitive surface. For the present, this type of tube must be regarded as a purely experimental device because of the difficulties of producing commercially screens free from blemishes, due to irregular electrical leakage between the mosaic elements and the base screen. There is every reason to believe, however, that this type of tube can be made commercially available in the near future.

CONCLUSION

In conclusion, it may be said that the iconoscope has, in actual field test, proved itself to be a very practical pick-up device in spite of its low theoretical efficiency. The tube has been accepted as the sole pick-up equipment in several extensive television broadcast projects, both in the United States and abroad, and has been rapidly gaining general recognition. It would, nevertheless, be very desirable to increase the sensitivity of the iconoscope, and this paper describes several methods by which this may be accomplished. Before these principles can be incorporated in tubes to be used for broadcast purposes, a great deal of research and development work must be done. Eventually, however, it will be possible to produce a tube which will operate at even lower light levels than at present.

The work described has been possible only through the co-operation of the members of the research staffs of both the Victor and the Radiotron Divisions of the RCA Manufacturing Co. Particular mention should be made of the work of the late Mr. G. N. Ogloblinsky and that of Messrs. H. Iams and A. W. Vance, who have contributed so materially to the developments described in this paper.

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